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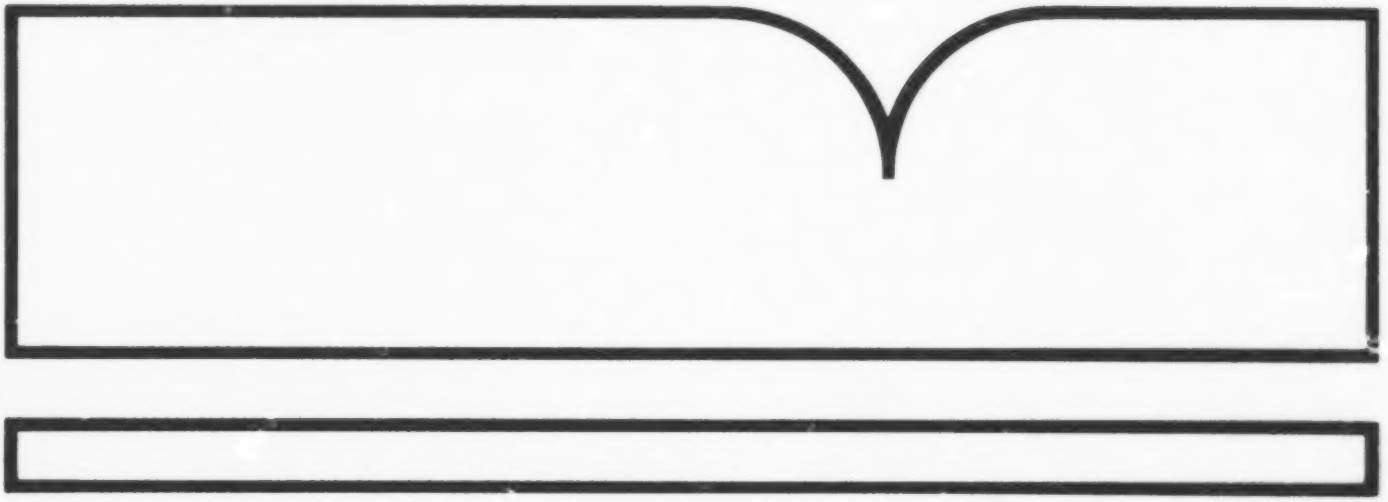

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ATMOSPHERIC DISPERSION MODELING BASED UPON BOUNDARY LAYER PARAMETERIZATION

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16. ABSTRACT

Characteristic scaling parameters in the planetary boundary layer have been applied to estimate the dispersion of nonbuoyant gaseous pollutants. Vertical and lateral spread are treated separately, and the choice of parameters for the dispersion models depends upon the actual state of the planetary boundary layer. The lateral concentration distribution at the surface was usually found to be a Gaussian distribution. The vertical concentration distribution was more often other than Gaussian.

For the different scaling regions of the atmosphere, methods are proposed for estimating the crosswind integrated concentrations, as functions of distance from the source, and are compared using results from tracer experiments. The proposed methods estimate the transport and dispersion directly from the turbulent state of the atmosphere. In all the scaling regions, the various methods adequately estimated the observed concentrations. The turbulence, and thus the dispersion, is better explained and modeled in the surface layer of the atmosphere (stable and unstable), than within the layers above the surface layer. Some success was demonstrated for releases in the stable local scaling (z-less) layer, and in the mixed layer and the near-neutral layer.

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ATMOSPHERIC DISPERSION MODELING BASED UPON BOUNDARY LAYER PARAMETERIZATION

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INTRODUCTION

Characteristic scaling parameters in the planetary boundary layer (PBL), as presented by Irwin et al. (1985) and Holtslag et al. (1985), have been applied to estimate the dispersion of nonbuoyant gaseous pollutants. Where only standard surface data are available, methods are suggested for estimation of wind and temperature profiles (Irwin et al., 1985).

Vertical and lateral spread is treated separately, and the choice of parameters for the dispersion models depends upon the actual state of the atmospheric boundary layer. The concentration distribution in the lateral direction is usually taken to be Gaussian, while for the vertical, several different approaches are suggested.

To illustrate the application of the boundary layer scaling parameters used in dispersion estimates, results from several dispersion experiments under different atmospheric conditions have been used.

THE STATES OF THE PBL

In the different idealized states of PBL, different scaling parameters describes the dispersion of passive gaseous air pollutants. A discussion of the division of the PBL is given by Olesen et al. (1984), and Holtslag et al. (1985). With three length scales:

z = height above the surface
h = mixing height
L = Monin-Obukhov length

it is possible to establish two independent dimensionless parameters:

z/h which is a relative height, and
h/L which is a stability parameter for the whole mixing layer depth (h).

Figure 1 summarizes schematically the limits of validity of the different scaling techniques distinguishing between regions commonly mentioned in the literature. The scheme has been discussed in greater detail by Holtslag et al. (1985).

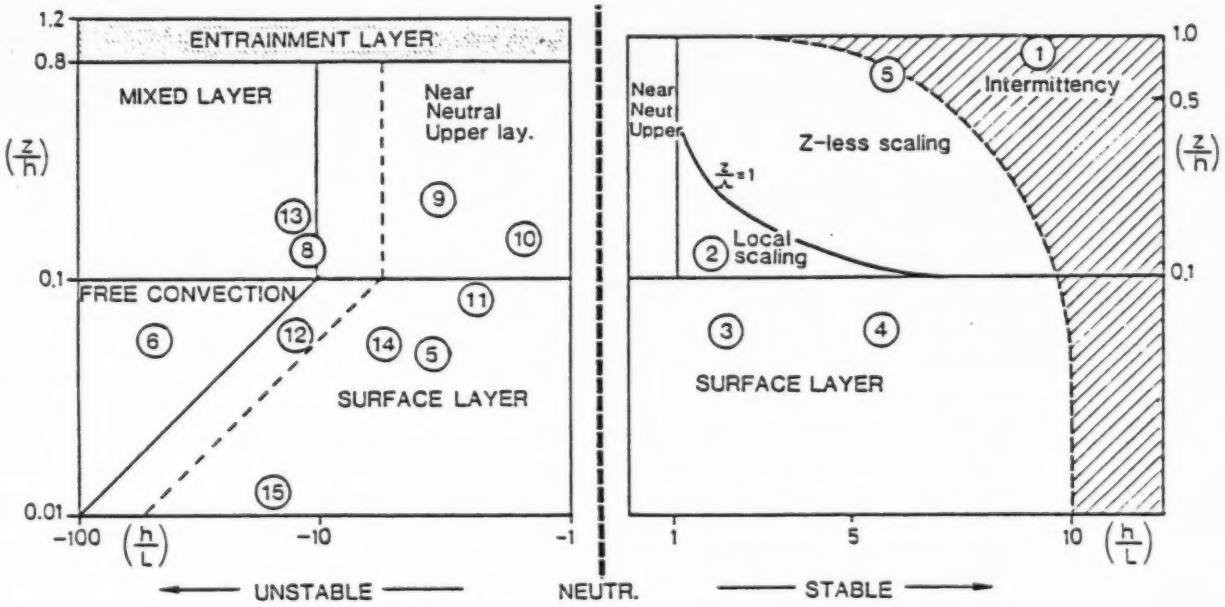

Fig. 1. A schematic view of the different scaling regions for unstable and stable atmospheric boundary layers. The numbers indicate where the different dispersion experiments fall within each region.

To obtain the Monin-Obukhov length, L, it is necessary to estimate the friction velocity, u_*, which is a function of the surface roughness, z_o .

In this paper, L is estimated from measurements of windspeed at one level and the temperature difference between two levels. From Monin-Obukhov theory for the atmospheric surface layer:

$$L = u_* T/(k\ g\ \theta_*) \qquad (1)$$

where θ_* is the surface layer scaling temperature, T is the ambient air temperature, k is the von Karman constant ~0.4 and g the acceleration of gravity.

Applying this so-called profile method, the vertical profiles of wind speed, $U(z)$, and potential temperature, $\theta(z)$, can be expressed as functions of u_*, θ_*, z_o and L in the surface layer (McBean, 1979).

At low winds and stable conditions, L is often less than 10 m. The surface layer is thus very shallow, and pollutants are often released above the surface layer. Above this thin, stable surface layer the turbulent mixing of pollutants is not so well described and documented as in the surface layer. Using a local Obukhov length, Λ, (described by Nieuwstadt 1984), the turbulence can be expressed as functions of z/Λ. For larger values of z/Λ turbulence is no longer described by z (z-less layer). For still larger stabilities, the present similarity theories break down, and the transport and dispersion of pollutants has to be described by other processes, usually difficult to characterize.

DISPERSION EXPERIMENTS

For comparison of model predictions with observed data, to demonstrate the performance of the proposed model, results from several dispersion experiments were used. The experiments were carried out at various sites. For stable cases we used data from Sivertsen, (1978) and Sivertsen and Bøhler, (1985) from two sites in relatively flat residential areas where the surface roughness $z_o \simeq 0.5$m. Data from the northern section of Copenhagen by Gryning and Lyck (1984) were collected over residential areas with an estimated z_o~0.6m. Sulphurhexafluoride (SF_6) was used as a tracer in one experiment, the freon $CBrF_3$ was released at a second level during stable atmospheric conditions. The Copenhagen tracer concentrations are 60-min. averages, while the concentrations during stable conditions represent 15-min. averages. All corresponding meteorological data have similar averaging times.

A summary of meteorological conditions during the experiments is presented in Table 1 for stable atmospheric conditions ($L>0$), and in Table 2 for unstable conditions ($L<0$). The different scaling regions for each experiment are also indicated in Figure 1.

Table 1: Summary of parameters for dispersion experiments carried out in stable atmospheric conditions.

	Experiment	z_s (m)	h (m)	U_s ms^{-1}	$\Delta\theta$ deg	L m	u_* ms^{-1}	σ_v ms^{-1}	z_s/h	z_s/L	h/L	"Region" (Fig. 1)
1	4 Jan 84	10	~6	0.5	0.1	0.7	0.026	0.36	0.8	14	8.4	Interm.
2	5 Jan 84	10	~90	0.9	0.09	60	0.09	0.17	0.11	0.16	1.5	Local sc.
3	7 Sep 84	1	11	1.0	0.71	5.3	0.036	1.1	0.09	0.19	2.1	Surf.l.
4	7 Feb 85	1	12	0.5	0.12	2.2	0.039	0.48	0.08	0.45	5.5	Surf.l.
5	7 Feb 85	11	12	0.5	0.12	2.2	0.039	0.48	0.8	4.5	5.5	z-less

Table 2: Summary of parameters for experiments carried out in unstable atmospheric conditions.
Experiments 6-14: release at z_s = 115 m; exp. 15: z_s = 1 m.

Experiment No		h (m)	U_s (ms^{-1})	L (m)	u_* (ms^{-1})	σ_v (ms^{-1})	σ_w (ms^{-1})	(z_s/h)	-h/L	"Region" (Fig. 1)
6	20 Sept 78	1980	3.4	- 46	0.37	0.98	0.83	0.058	43	Free conv.
7	26 Sept 78	1920	10.6	-348	0.74	1.39	1.07	0.06	5	Surf.layer
8	19 Oct 78	1120	5.0	-108	0.39	0.85	0.68	0.103	10	Mixed layer
9	3 Nov 78	820	4.6	-173	0.39	0.47	0.47	0.293	2.3	Near neut.
10	9 Nov 78	820	6.7	-577	0.46	0.77	0.71	0.140	1.4	Near neut.
11	30 Apr 78	1300	13.2	-569	1.07	2.26	1.33	0.088	2.3	Surf.layer
12	27 Jun 78	1850	7.6	-136	0.64	1.61	0.87	0.062	14	Surf.layer
13	6 Jul 78	810	9.4	- 72	0.70	1.35	0.72	0.142	11	Mixed layer
14	19 Jul 78	2090	10.5	-382	0.77	1.71	0.98	0.055	5	Surf.layer
15	6 Jun 78	700	4.0	- 42	0.83	1.2	-	0.003	16	Surf.layer

DISPERSION ESTIMATES

Lateral dispersion

Most dispersion experiments showed that the lateral distribution of the plume usually resembles a Gaussian distribution (e.g., Sivertsen, 1978; Gryning and Lyck, 1984). Figure 2 shows that even under very stable conditions, with releases of tracers in and above the surface layer, the lateral concentration distribution near the surface is close to Gaussian.

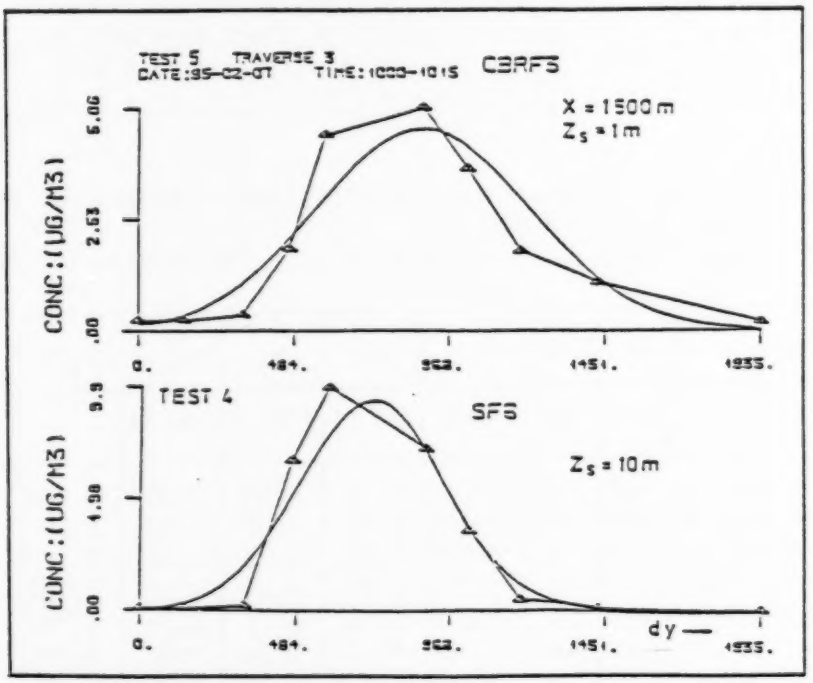

Fig. 2. The lateral crosswind concentration distributions at a distance x = 1500 m, of SF_6 released at z_s = 10 m, and $CBrF_3$ released at z_s = 1 m during stable atmospheric conditions. (Δ=observed, and best fit estimated Gaussian distributions).

Pasquill (1971) derived from Taylor's statistical theory for plume dispersion the following expression, for estimating the standard deviation of the lateral crosswind concentration distribution:

$$\sigma_y = \sigma_v \, t \, f_y \, (t, T_y) \qquad (2)$$

where f_y is a universal function of transport time, t, and a time scale, T_y, for the dispersion process. Draxler's (1976) scheme was found by Irwin (1983) to perform best when:

$$f_y = (1 + 0.9\ (t/T_y)^{0.5})^{-1} \qquad (3)$$

Eq. (3) is also in agreement with the findings of Gryning and Lyck (1984), and Sivertsen (1978). For practical use it is suggested that T_y ~ 1000 s for elevated sources, and T_y ~ 300 s for ground-level sources. The standard deviation of wind fluctuation, σ_v, (or wind direction fluctuation σ_θ) should be measured directly. For the tracer experiments described here, σ_v and σ_θ were measured over an averaging time, corresponding to the measured concentrations. If the wind fluctuations are not measured directly, σ_v can be estimated from u_*, L and h, as given by Irwin et al. (1985) and Holtslag et al. (1985).

$$(\sigma_v/u_*)^2 = 0.7(-h/L)^{2/3} + 2.7(1-z/h)^2/(1+2.8z/h)^{2/3} \qquad (4)$$

In the following, methods are given for estimating crosswind integrated concentrations $X_y(x)$, at a distance, x, for the different regimes presented in Figure 1. When these values of X_y are estimated from the various scaling parameters, the concentration at a given point downwind, X(x,y), can be calculated from:

$$X(x,y) = X_y \exp(-y^2/2\sigma_y^2)/(\sigma_y\ (2\pi)^{1/2}) \qquad (5)$$

This method is capable of treating non-Gaussian vertical concentrations distributions.

Stable conditions

Turbulent dispersion in the stable boundary layer is not as well understood as in the unstable boundary layer. This is especially the case for elevated sources, when the wind weakens to less than ~ 1 m/s during surface inversions. Since the similarity profiles are only valid for $z_o << z < L$, and L often is less than ~ 10 m, the profile method, mentioned above , should only be applied to a shallow layer of the atmosphere. The temperature difference should be measured directly.

At the bottom is a mixed layer of thickness h. There is some controversy as to whether simple equations for h as a function of friction velocity $u_*(z_o)$, and stability, L, can be applied (Panofsky and Dutton, 1984). The most common formula for h was first suggested by Zilitinkevich (1972):

$$h = a(u_* L/f)^{0.5} \qquad (6)$$

where f is the Coriolis parameter, and a = 0.4. Nieuwstadt (1984) showed that there was reasonable agreement between estimates obtained with Eq.(6) and observations in level terrain, when drainage effects are negligible.

The stable surface layer. In the stable surface layer, where $(z/h) \leq 0.1$, the Monin-Obukhov theory applies. Most turbulent quantities are described by z/L. The vertical eddy diffusivity for matter is described by:

$$K = k\, u_* \, z/\phi_h(z/L) \qquad (7)$$

where ϕ_h is an empirical function of stability z/L.

Assuming that the vertical profiles of K(z) and the wind speed u(z) can be represented by power laws, a general solution of the two-dimensional dispersion equation can be written (van Ulden, 1978; Gryning et al. (1983):

$$X_y(z)/Q = (A/\bar{z}\bar{u}) \exp[-(Bz/\bar{z})^s] \qquad (8)$$

where A and B are functions of the shape parameter s. The mean height of the gas cloud, $\bar{z}$, and the mean wind speed, $\bar{u}$, transporting the cloud is determined iteratively as a function of the downwind distance x. Further details can be found in Irwin et al. (1985), and Holtslag et al. (1985)).

For the tracer experiments (Nos. 3 and 4 in Table 1) in the stable surface layer the estimated crosswind integrated concentration X_y at z = 1 m, was in good agreement with measurements, as shown in Figure 3.

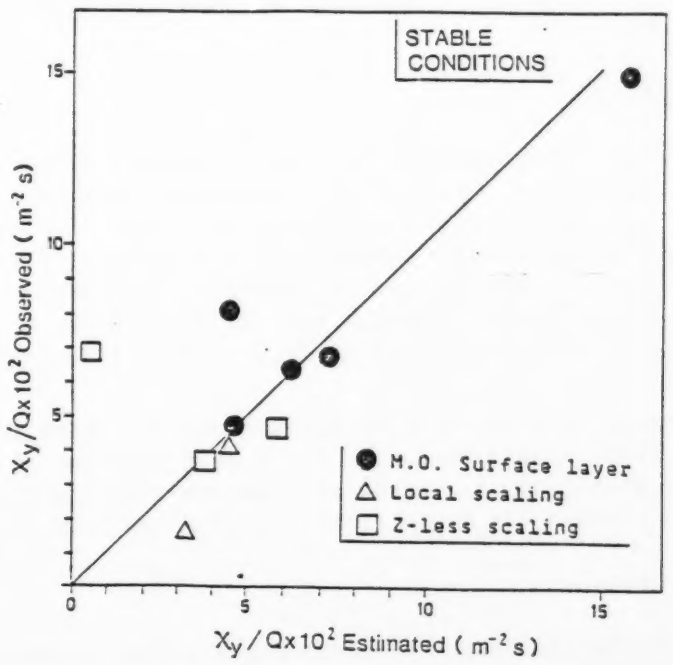

Fig. 3. Estimated versus observed crosswind integrated concentrations during stable atmospheric conditions.

In these experiments, the temperature difference was measured between 10 and 2 m over a snow surface, while the transport and dispersion of tracers occured over a residential area with an estimated surface roughness of $z_o \sim 0.5$ m. The measured potential temperature profile had to be modified to a gradient normally found in build-up areas ($\Delta\theta \sim 0.1$-0.2 deg.).

Local and z-less scaling region. Above the thin stable surface layer, the turbulent mixing of pollutants is not as well described and documented as in the surface layer. Experiments reported by Venkatram et al. (1984) and approaches presented by Nieuwstadt (1984), show that local z-less scaling arguments can be employed to describe the dispersion process.

The local Obukhov length Λ can then be written as:

$$\Lambda = -\tau^{3/2}/(k\ \overline{w\theta}\ (g/T)) \qquad (9)$$

where τ is the kinematic stress.

For applications of local and z-less scaling in dispersion estimates, vertical profiles of τ and $\overline{w\theta}$ are needed. These were obtained by Nieuwstadt (1984) by modeling the evolution of the stable boundary layer, and using a closure hypothesis of a critical Richardson number, Ri = 0.2. This lead to a simple expression for Λ/L:

$$\Lambda/L = (1-z/h)^{5/4} \qquad (10)$$

with h as given in Eq. 6. The limits of validity of the different scaling techniques in the stable PBL, as presented in Figure 1, are taken from the work of Holtslag and Nieuwstadt (reported by Holtslag et al. 1985).

To characterize the dispersion in these regions, the use of a Gaussian-type plume model is recommended. Direct measurements of σ_v and σ_w are preferred and strongly recommended in these layers. The averaging times should correspond to the averaging times associated to the concentration estimates.These values can also be applied in expressions such as Eq. 2 and 3 for the vertical spread. Irwin (1983) found that the dispersion time scale for vertical diffusion, T_L, is of the order of 50 s. Venkatram et al. (1984) reported from dispersion experiments, that the vertical dispersion for "elevated releases" could be expressed as:

$$\sigma_z = \sigma_w\ t(1 + t/2T_L)^{-0.5} \qquad (11)$$

where T_L was approximately 8 to 12 s. In our stable layer experiments (reported below) we found a better fit to data using Eq. 3, with T_L= 50 s. If σ_w is not measured directly, we suggest the use of Nieuwstadt's (1984)

modified Monin-Obukhov theory, with local scaling, which describes the upper part of the stable boundary layer. Vertical profiles of τ and $\overline{w\theta}$ give a complete description of the vertical structure of turbulence in the stable atmosphere:

$$\sigma_w = 1.3\ u_*(1-z/h)^{3/4} \qquad (12)$$

where $1.3\ u_*$ is the value of σ_w in the surface layer.

For experiment 2, where we use Eq. 12 for σ_w in the local scaling region, the estimated crosswind integrated concentrations are in good agreement with observations, as shown in Table 3 and in Figure 3.

In one experiment the SF_6 tracer was released in the z-less scaling region, and at the same time as another tracer, $CBrF_3$, was released in the surface layer. (experiment 5 Table 1). The behaviour of the SF_6 tracer released in the z-less scaling region is complicated to explain. The vertical spread of SF_6 released into the z-less region does not nicely follow the theoretical framework.

Two approaches were examined, as presented in Figure 4. When using the z-less scaling Eq. 12 for σ_w, the cro· wind integrated concentration at the closest sampling array (x= 300 m) is underestimated, while at the sampling arrays further away, the observations can be reasonably reproduced. This might be caused by intermittent downwash of SF_6 to the surface, which could affect the average concentrations when the sampling time is only 15 min.

It is also possible that the plume spreading over the village area actually followed a surface layer behaviour. The second estimate (line b in Figure 4) of crosswind integrated concentrations with distance, is therefore based upon an estimated $\sigma_w = 1.3\ u_*$ in the surface layer. As can be seen from Figure 4, these estimates might explain the total behaviour of the SF_6 released at the upper part of the boundary layer (at $z \simeq 0.8\ h$).

For the case when the tracer was released above the stable boundary layer (at $z_s > h > L$) (experiment 1, Table 1) apparently the turbulence becomes intermittent and the dispersion process is not well described.

The approach by Venkatram et al. (1984) was tested in this case with

$$\sigma_z = (2K_z t)^{1/2} \text{ for } t >> T_L \qquad (13)$$

and

$$K_z \simeq K_H = u_*^2/N(\beta)^{1/2} \qquad (14)$$

Table 3: Observed and estimated cross wind integrated concentrations, (X_y/Q), for the dispersion experiments during stable atmospheric conditions.

Experiment		Distance from source (m)	(X_y/Q) (m^{-2} s) Observed	Estimated	"Scaling-region"
1	4 Jan 84	700	$1.8\ 10^{-3}$	(10^{-4})	
		1400	$1.1\ 10^{-3}$	($3\ 10^{-3}$)	"Elevated Source"
2	5 Jan 84	700	0.044	0.042	Local scaling
		1400	0.015	0.03	
3	7 Sep 84	780	0.065	0.062	Surface layer
		1140	0.084	0.042	
		300	0.16	0.15	
4	7 Feb 85	700	0.065	0.073	Surface layer
		1500	0.044	0.047	
		300	0.07	0.0003	
5	7 Feb 85	700	0.033	0.038	z-less-layer
		1500	0.044	0.06	

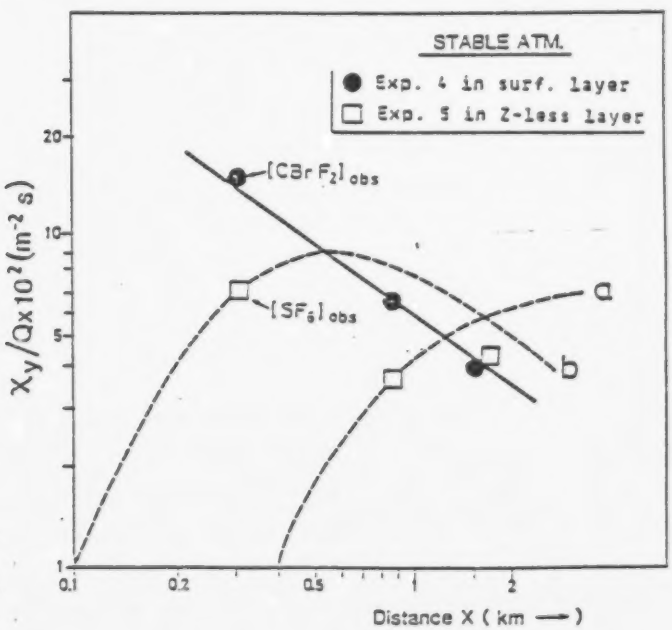

Fig. 4. Crosswind integrated concentrations (X_y/Q) as a function of distance during experiment 4 and 5 on 7 Feb 1985.
Observed $CBrF_3$ released in the surface layer
Observed SF_6 released in the z-less layer
a) estimated X_y/Q with $\sigma_w = 1.3u_* (1-z/h)^{3/4}$
b) estimated X_y/Q with $\sigma_w = 1.3u_*$

where N is the Brunt Väisälä frequency $(g\Delta\theta/\Delta z\ T_o)^{1/2}$, and $\beta = 4.7$. The estimated crosswind integrated concentrations are given in Table 3 (in parentheses), and show that the measured values in this case are not well reproduced.

Unstable conditions

The characterization of turbulence within the unstable boundary layer is better understood and documented than in the stable counterpart. The important scaling parameters for description of turbulent diffusion are different in the different scaling regions as indicated in Figure 1. The parameters are presented and discussed by Irwin et al. (1985) and Holtslag et al. (1985), and will not be repeated here.

In the following we will examine data from the dispersion experiments 6-15 presented in Table 2.

The unstable surface layer. In the unstable surface layer, given by $z/h < 0.1$ and $-z/L < 1$, the Monin-Obukhov theory applies, and the dispersion can be described by the same set of equations as given for the stable surface layer (Eqs. 7-8). The empirical functions and parameters might be different, as shown, e.g., by Businger, (1973); Dyer, (1974); Irwin et al. (1985).

Five dispersion experiments with SF_6 as tracer were examined, and the crosswind integrated concentrations (X_y^6/Q) were estimated from Eq 8. The comparison with observed X_y/Q is given in Table 4 and also summarized in Figure 5.

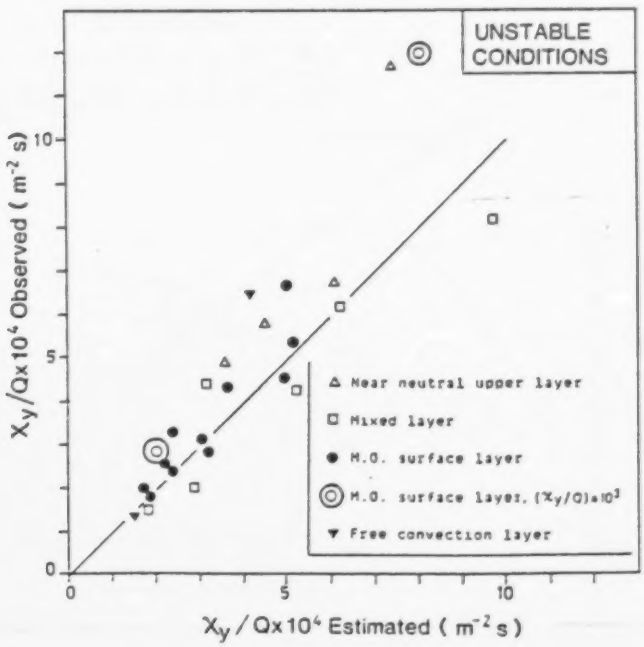

Fig. 5. Estimated versus observed crosswind integrated concentrations (X_y/Q) during unstable atmospheric conditions.

Table 4: Summary of observed vs. estimated crosswind integrated concentrations.

"Scaling region"	Exper. No.	Distance from source (km)	$X_y/(Q\ 10^4)(m^{-2}s)$	
			Observed	Estimated
Surf. layer	7	2.1	5.38	5.18
		4.2	2.95	3.20
	11	2.0	3.96	3.69
		4.2	2.22	2.37
		5.9	1.83	1.81
	12	2.0	6.70	5.02
		4.1	3.25	2.43
		5.3	2.23	1.77
	14	2.1	4.58	4.98
		4.2	3.11	3.07
		6.0	2.59	2.22
	15	0.13	120.	80.
		0.85	28.	20.
Free conv.	6	1.9	6.48	4.23
		3.7	2.31	1.56
Mixed Layer	8	1.9	8.20	10.3
		3.7	6.22	6.24
		5.4	4.30	3.4
	13	1.9	4.16	5.7
		3.6	2.02	3.1
		5.3	1.52	1.8
Near neutral upper layer	9	4.0	11.61	7.38
	10	2.1	6.72	6.11
		4.2	5.82	4.51
		6.1	4.93	3.61

The agreement between observed and estimated concentrations in the unstable surface layer is good, even if there seem to be a slight tendency of underestimating.

The mixed layer. Mixed layer scaling is found appropriate for $0.1 < z/h < 0.8$ and $-h/L \geq 10$. Briggs (1984) reanalyzed the laboratory simulations reported by Willis and Deardorff (1978), and Lamb (1978) and found that the mean crosswind integrated dimensionless concentration could be expressed by (Irwin et al. 1985):

$$X_y\, h\, U/Q = 0.9\, X^{9/2} \cdot z_s^{-11/2} \left[z_s^{-3/4} + 0.4 \cdot X^{9/2} \cdot z_s^{-9/2}\right]^{-4/3} + \left[1 + 3z_s^{1/2}\, X^{-3/2} + 50X^{-9/2}\right]^{-1} \qquad (15)$$

where $X = (x/h)(w_*/U)$, (16)

z_s is the source height, $z_s = (z_s/h)$ and $w_* = (g\, h\, \overline{w'\theta'_o}\, /T)^{1/3}$ is the convective velocity scale for the turbulence. Eq. 15 applies for non-buoyant releases when $0.04 < z_s < 1$.

The dimensionless distance, as given in eq. 16 gave crosswind integrated concentrations which were underestimated, especially at the longer distances. Briggs' interpolation curves had to be shifted towards higher values of X. Figure 6 shows the comparison between observations and estimates where the observed values were given by:

$$X = 0.6(x/h)(w_*/U) \qquad (17)$$

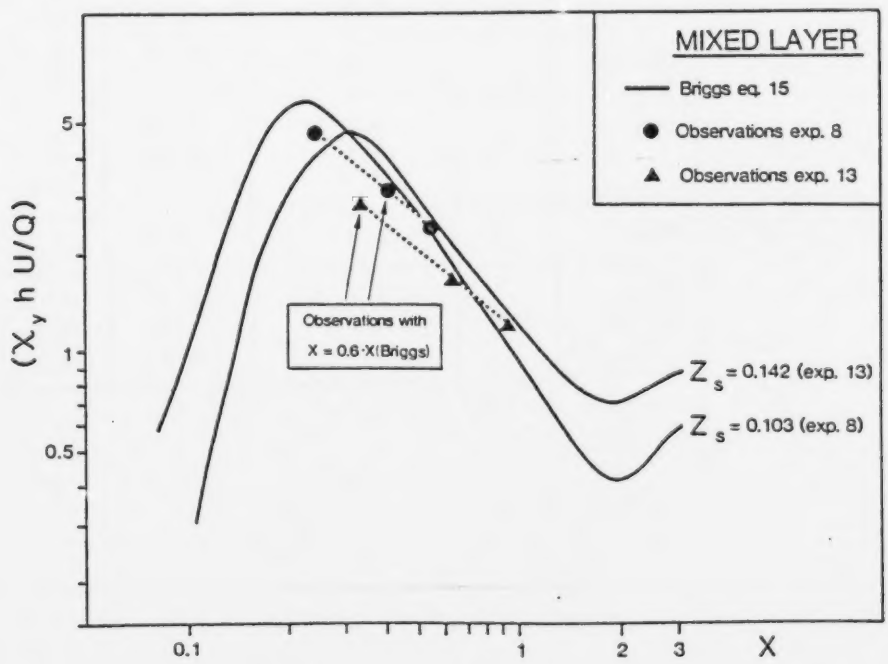

Fig. 6. Observations and estimates in the Mixed layer of normalized crosswind concentrations (X_y h U/Q) as a function of a normalized distance X. The curves show Briggs' interpolation formula (Eq. 15) with $X = 0.6(x/h)(w_*/U)$ for the observations.

The estimates are in good agreement with observations, even if for experiment 13 the constant in eq. 17 should be between 0.6 and 0.8.

The free convection layer. The free convection layer is apparent above the surface layer, typically for z>-L and below z ~ 0.1 h. The controlling parameters z and the surface heat flux $\overline{w'\theta'_o}$ describe a scaling velocity (Tennekes, 1970):

$$u_f = (\overline{w'\theta'_o}\, zg/T)^{1/3} \qquad (18)$$

The normalized crosswind integrated concentration is given by:

$$X_y\, Uz/Q = b((u_f/U)(x/z))^{-3/2} \qquad (19)$$

where b = 0.9. The free convection similarity scaling was found to apply for downwind distances of $0.03 < (u_f/U)(x/z) < 0.23$ (Nieuwstadt, 1980). Only one experiment in the free convection layer is considered in this paper. The results in Table 4 indicate that Eq. 19 underestimates the crosswind concentrations. The reason for this might be that the normalized distances to the concentration sampling arrays were outside the range of applicability that was found by Nieuwstadt (1980) from Prairie Grass data.

The near neutral upper layer. In the near neutral upper layer, where -L becomes large ($-h/L < 10$) and $0.1 < (z/h) < 0.8$, direct measurements of σ_w and σ_v are recommended. These values can be applied in Gaussian type dispersion models with σ_y and σ_z as given in Eqs. 2 and 11, respectively.

Otherwise σ_w and σ_v could be approximated from profiles of lateral and vertical variances given by eq. 4 or by:

$$(\sigma_w/u_*)=1.54[z/(-kL)]^{2/3} \exp(-2z/h)+1.457(1-z/h)^2 \qquad (20)$$

The estimates of crosswind integrated concentration, from experiments 9 and 10 in the near neutral upper layer, are compared with observations in Table 4. The Gaussian model, with

$$f_z = (1 + 0.9(t/T_L)^{0.5})^{-1} \qquad (21)$$

and T_L = 500 s (see Eqs. 2 and 3), slightly underestimated the observed concentrations (within ~ 30%).

DISCUSSION

The diffusion of non buoyant gaseous pollutants has been described by different scaling parameters in the different "regions" of the planetary boundary layer.

The lateral dispersion was usually found to approach a Gaussian

distribution. In the vertical, however, the concentration distributions can be far from Gaussian.

For the different scaling regions of the atmosphere, methods with different parameters for estimating the crosswind integrated concentrations, as functions of distance from the source, have been suggested and tested versus results from tracer experiments. The parameters were estimated from meteorological measurements directly. In this way the transport and dispersion has been directly related to the turbulent state of the atmosphere.

In all scaling regions, for which tracer data were available, the various methods adequately estimated the observed concentrations. This is shown in Figure 3 for the stable PBL and in Figure 5 for the unstable PBL. The turbulence, and thus the dispersion, is better explained and modelled in the surface layer of the atmosphere (stable and unstable), than when the releases are above the surface layer. Some success was demonstrated also in the stable local scaling (and z-less) layer, and in the mixed- and near-neutral upper layer. There is (as seen from Figure 6) a tendency of underestimating the observed crosswind concentrations, when Eq. 16 was used to define X. The adjustment suggested in Eq. 17 improves the performance for estimating concentrations values for releases within the unstable mixed layer.

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